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Photoluminescence of the GaAs Superlattices with Quasi-Delta-Doped Layers

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Abstract: The GaAs short-period superlattices have been grown for the first time by the metal-organic hydride epitaxy method using Se and C for quasi-δ-doping. Photoluminescence spectra measured at 4.2 K display well-distinguished peaks, which coincide with transitions between quantizied levels of electrons and holes in the potential relief quantum wells. To describe observed phenomena in quasi-δ-doped superlattices a theory is developed with taking into account existing tails of the density of states.

Keywords: GaAs, superlattice, δ-doping, quantum well, photoluminescence, tunability.

INTRODUCTION

Doping superlattices, or *n-i-p-i* crystals, have advanced properties for the development of novel optoelectronic devices. The δ-doping technology extends possibilities of the superlattice design and allows improving the characteristics compared with homogeneously doped *n-i-p-i* structures. For the δ-doping, molecular-beam epitaxy is most widely applied [1]. The GaAs δ-doped superlattices were also grown by metal-organic vapor-phase epitaxy [2, 3]. For *n*- and *p*-type δ-doping, impurities Si and C were used and for obtained superlattices the tunable low-temperature photoluminescence (PL) was demonstrated.

Tunable *n-i-p-i* structures are attractive for integration with different optoelectronic devices, such as photoelectric detectors [4], quantum cascade lasers [5], or photonic crystal heterostructures [6]. Besides, δ-doped superlattices provide effective operation parameters and extent functional characteristics of photodetectors [7], modulators [8-10], and nonlinear optical switches [11-13].

In this work, the GaAs short-period superlattices have been grown for the first time by the metal-organic hydride epitaxy method using Se and C for quasi-δ-doping. Earlier, such a method was applied for making the photosensitive heterostructures with the GaInAs quantum-well spacer [14]. For the obtained superlattices, low-temperature PL spectra were measured and a theory for describing the observed phenomena was developed.

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EXPERIMENTAL

The formed GaAs quasi-δ-doped superlattices have the 30-period *n-i-p-i* set of doped *n*- and *p*-type layers and undoped *i*-layers. The superlattice period d was 19 or 29 nm and *i*-layers were, accordingly, of the order of 7 or 11 nm. The structure thickness was 0.8 or 1.2 μm, including the 0.2-μm buffer layer and 0.1-μm top layer. The sheet concentrations of donors Se in the *n*-layers and of acceptors C in the *p*-layers made up $(1.5\text{-}1.6)\times10^{13}$ cm^{-2}.

The PL characteristics of the grown δ-doped superlattices were measured at CW excitation by the 488-nm radiation of an Ar^+-ion laser. At the structure temperature $T = 77$ K in the spectral region near 1.4 eV, a tunable PL band in dependence on power excitation is observed [15]. The PL spectrum for the longer-period structures is shifted to the long-wavelength region and its tuning bandwidth is larger as compared the shorter-period structures. Since the *i*-layers in the first structures is approximately in one and a half times thicker than for another structures, the superlattice effective energy band gap must be smaller for the first ones and it exhibits a greater tunability under optical excitation. In addition, it provides a narrower linewidth of the PL spectrum.

The PL spectra measured at 4.2 K (Fig. **1**) display a structure shape with well-distinguished peaks, which coincide with allowed optical transitions between quantizied levels of electrons and holes in the potential relief quantum wells. Such a behavior has been also observed for structures grown by gas-source molecular-beam epitaxy [16].

THEORY

To describe observed PL phenomena in quasi-δ-doped superlattices, we used the simulation procedure previously

developed and successfully applied for the description of PL spectra of homogeneously and δ-doped superlattices as well [17, 18]. The theory with taking into account existing tails of the density of states explains adequately experimental observations of the tuning and transformation of PL spectra and shows that at increasing the temperature the quantized character of the spectra is diminished.

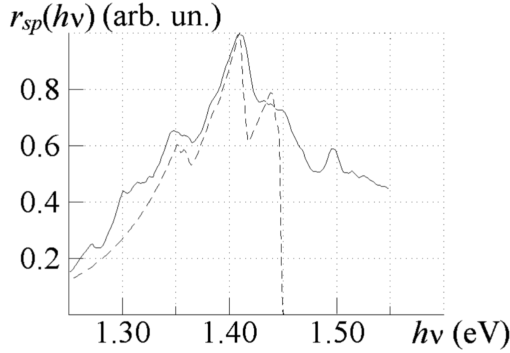

Fig. (1). The PL spectrum $r_{sp}(h\nu)$ of the quasi-δ-doped GaAs *n-i-p-i* structure at T = 4.2 K as compared a calculated spontaneous emission recombination spectrum (the dashed curve) at ΔF = 1.472 eV.

As seen from Fig. (**1**), the best fitting between experimental and calculated PL spectra occurs where the superlattice design parameters are assumed to be as followed, *i. e*., acceptor concentration $N_a = 5.17\times10^{19}$ cm^{-3}, donor concentration $N_d = 1.5\times10^{20}$ cm^{-3}, *p*-layer thickness d_p = 2.9 nm, *n*-layer thickness d_n = 1 nm, *i*-layer thickness d_i = 5.55 nm, number of periods N_p = 10, effective electron mass $m_c = 0.067m_e$, effective heavy hole mass $m_{vh} = 0.34m_e$, effective light hole mass $m_{vl} = 0.094m_e$, transverse heavy hole mass $m_{vh\perp} = 0.11m_e$, transverse light hole mass $m_{vl\perp} = 0.20m_e$. If a superlattice is excited up to the value of the quasi-Fermi level difference ΔF of $\simeq$ 1.47 eV at T = 4.2 K, the effective energy gap E'_g equals $\simeq$ 1.04 eV and the potential profile depth $2\Delta V \simeq$ 0.45 eV. In this case, distribution of quantized electron and hole levels in the periodic quantum wells is shown in Fig. (**2**).

Obviously, not only the population of the excited subband states determines the intensity and shape of the emission band of the structures but also the strength of overlapping the electron and hole envelope wave functions is essential. Comparison of the observed PL spectrum and the numerical simulated shape of the recombination emission band shows that more intensive transitions occur through the ground subband of electrons (the quantum number n = 0) and light hole states with quantum numbers m = 0, 1. At high enough excitation, significant value has transitions involving excited electron states (n = 1) and ground subbands of heavy and light holes (m = 0). For the optical transitions through the light hole subband, the squired overlap integral of the electron and hole envelope wave functions $|I_{nm}|^2$ has the highest value (see Table **1**).

Character of a tunability of the PL band and transformation of its shape under excitation of the superlattice at different temperatures are shown in Fig. (**3**). Increasing the temperature results in a smooth of the PL band. The tuning bandwidth reaches up to 0.4 eV.

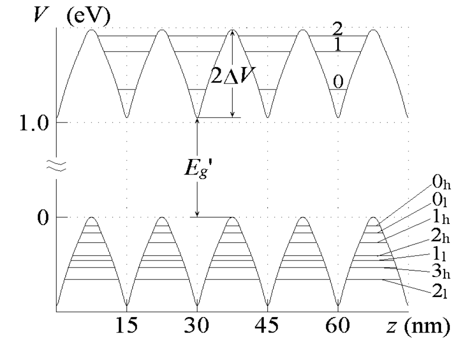

Fig. (2). Potential profile $V(z)$ of the modeling *n-i-p-i* structure and energy levels of electrons and heavy (h) and light (l) holes. T = 4.2 K, ΔF = 1.472 eV.

However, it has to mention that at low excitation power the intensity of the tunable PL band markedly decreases and a broad emission band in the range of 1 eV masks it. The observed additional broad PL band can be attributed to deep levels of residual impurities or related complexes [15]. Available peaks at the short-wavelength edge of the tunable PL band are evidently related to carbon, exciton recombination, and direct band-band transitions.

Table 1. Energies of Optical Transitions $h\nu_{nm}$ Between Electron (E_{cn}) and Heavy (h) or Light (l) Hole (E_{vm}) Energy States with Different Quantum Numbers n and m and the Miniband Wave Vector k_z = 0, π/d and Values of the Squared Overlap Integral of the Electron and Hole Envelop Wave Functions $|I_{nm}|^2$

$h\nu_{nm}$ (eV)	(n, m, k_z)	E_{cn} (eV)	E_{vm} (eV)	$\|I_{nm}\|^2$
1.221	(0,0h,0)	0.134	0.047	0.011
1.258	(0,0l,0)	0.134	0.084	0.048
1.309	(0,1h,π/d)	0.135	0.134	0.038
1.379	(0,2h,0)	0.134	0.205	0.109
1.402	(0,1l,π/d)	0.135	0.227	0.245
1.407	(1,0h,π/d)	0.319	0.048	0.207
1.442	(0,3h,π/d)	0.135	0.267	0.216
1.443	(1,0l,π/d)	0.319	0.084	0.388

ANALYTICAL APPROACH

Qualitative analysis can be provided in the frame of the sawtooth superlattice model [16, 19-21]. Analytical simulation of the redistribution of the energy subbands and, accordingly, of the optical transition quantum energies for a superlattice excited at low temperatures approves and supports conclusions based on the above described more complex numerical calculations.

In the effective impurity concentration approach, the potential relief depth $2\Delta V$ of a quasi-δ-doped superlattice is described by the relation [17]:

$$2\Delta V = 2\Delta V_0(1-r) = \frac{\pi e^2}{\varepsilon}\frac{N_\delta}{2}(d+2d_i)(1-r), \tag{1}$$

where ε is the dielectric constant, $N_\delta = N_d d_n = N_a d_p$, $r = n/N_\delta$ is the excitation factor, n is the non-equilibrium concentration of electrons. The energy of quantizied levels depends also on the superlattice excitation power. For a sawtooth potential relief, the level energies can be calculated with the high enough accuracy using the effective mass approximation and transforming the Schrödinger equation into the Airy differential equation [19-21]. The Airy function asymptotic expansion approach [19] and variational calculations [16] provide almost the same results for the lowest several confined states. For the electron states E_{cn} we have analytically:

$$E_{cn} = \left(\frac{3\pi}{4}\right)^{2/3}\left(n+\frac{1}{2}\right)^{2/3}\left(\frac{\pi e^2}{\varepsilon}\right)^{2/3}\left(\frac{2\hbar^2 N_\delta^2}{m_c}\right)^{1/3} \times (1-r)^{2/3} = E_{00}(2n+1)^{2/3}(1-r)^{2/3}, \quad (2)$$

where the quantum number n = 0, 1, 2, …, E_{00} is the ground electron state energy. Here, levels of the appeared minibands are not included, their width is assumed to be negligible small. Similar expressions are given for heavy and light hole states E_{vm}.

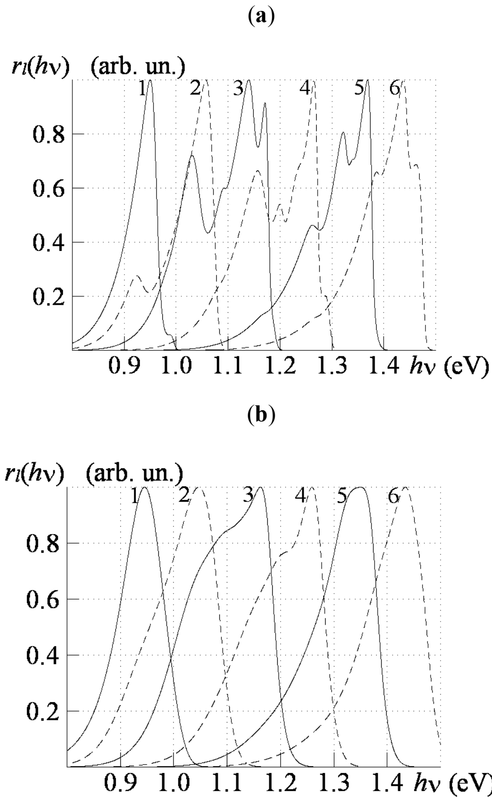

Fig. (3). Transformation of the PL spectrum $r_l(h\nu)$ of the *n-i-p-i* structure at different temperatures (**a**) T = 20 and (**b**) 77 K versus the quasi-Fermi level difference (1) ΔF = 1.0, (2) 1.1, (3) 1.2, (4) 1.3, (5) 1.4, and (6) 1.5 eV.

Thus, we obtain a simple expression for determining the energy $h\nu_{nm}$ of emitted quanta, which are associated with transitions between electron states E_{cn} and hole states E_{vm}, *i.e.*,

$$h\nu_{nm} = E_g - 2\Delta V_0(1-r) + E_{00}(1-r)^{2/3} \times \left((2n+1)^{2/3} + \left(\frac{m_c}{m_{vi}}\right)^{1/3}(2m+1)^{2/3}\right), \quad (3)$$

where E_g is the energy gap of the semiconductor, i = h, l is the hole index. As seen, at increasing the superlattice excitation the quantum energy $h\nu_{nm}$ approaches E_g since the potential relief depth decreases, and the energies of various optical transitions become closer as a result of decreasing the energy levels, which are involved in the transitions.

To find relation between the quasi-Fermi levels F_e and F_h and to evaluate the excitation factor r, we use the electroneutrality equation for degenerate conditions that are accomplished at low temperatures, *i. e.*,

$$m_c \sum_n \left(F_e - E_{c0} - E_{cn}\right) = \sum_{m,\,i} m_{vi\perp}\left(E_{v0} - E_{vm} - F_h\right), \quad (4)$$

where E_{c0} - E_{v0} = E'_g, F_e - $E_{c0} \geq E_{cn}$, E_{v0} - $F_h \geq E_{vm}$. In the parabolic band approximation, transverse components of effective hole masses are taken as $m_{vi\perp} = m_{vi}$. Calculations are carried out with the following parameters $N_\delta = 1.5\times10^{13}$ cm^{-2}, d = 19 nm, d_i = 6.8 nm, $m_c = 0.067 m_e$, $m_{vh} = 0.34 m_e$, $m_{vl} = 0.094 m_e$, E_g = 1.519 eV, ε = 12.5. In this case, the initial depth of the potential profile equals $2\Delta V_0$ = 0.885 eV.

At increasing the excitation of the superlattice, *e. g*., up to r = 0.45 and ΔF = 1.5 eV, the relief depth becomes $2\Delta V$ = 0.487 eV and current carriers occupy ground and excited electron subbands and only ground heavy and light hole subbands. Therewith, the effective energy gap E'_g = 1.032 eV and a set of allowed optical transitions includes quantum energies 1.256, 1.300, 1.408, and 1.452 eV. The energies 1.256 and 1.300 eV are attributed to transitions between the ground electron (n = 0) and heavy and light hole (m = 0) subbands, and the energies 1.408 and 1.452 eV are associated with transitions from the excited electron states (n = 1) to the ground (m = 0) heavy and light hole subbands, respectively. It is in accordance with data [16] and numerical more precise self-consistent calculations (see Table **1**).

CONCLUSION

Spectra of PL emission measured at 4.2 K display a structure shape with well-distinguished peaks, which coincide with allowed optical transitions between quantizied levels of electrons and holes in the potential relief quantum wells. The developed theory with taking into account tails of the density of states explains experimental observations and shows that at increasing the temperature the quantized spectra behavior becomes less pronounced. The main attribute of doping superlattices, *i. e*., tunability of the emission spectrum in dependence on the excitation power is observed in a wide range 1.3 to 1.5 eV at the structure temperature up to 77 K. Tunable performance of the *n-i-p-i* structures is important for extension of functional characteristics of various optoelectronic devices, including

photodetectors, modulators, amplifiers, lasers, light-emitting diodes, and nonlinear optical switches.

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